Re-mapping the 2004 Boxing Day Tsunami Inundation in the Banda Aceh Region with Attention to Probable Sea Level Rise

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Senior Integrative Exercise
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ABSTRACT

The effects of the Great Sumatra-Andaman Earthquake and the resulting tsunami on December 26, 2004 were greatest in the Banda Aceh region of northern Sumatra, where wave heights reached between 9 and 12 meters. Studies of the Sumatra-Andaman fault indicate that the fault will rupture again, probably within the next 100 years, putting the Banda Aceh region in danger of another tsunami. It is essential to the lives of all Acheans that an evacuation plan and an early warning tsunami system are established in Banda Aceh. To accomplish this, it is necessary to understand the extent and nature of 2004 inundation as well as understand the future risks to the area.

This study develops a model to describe the 2004 inundation of Banda Aceh from data collected by two teams of international scientists. It then projects future inundation limits and heights that may occur in Banda Aceh under the same initial seismic conditions as in 2004, but with sea level rise due to climate change and earthquake related subsidence. This study also models possible tsunami inundation limits and heights under probable future seismic events. Results suggest that changes in sea level on the scale of 3 meters have the potential to cause inundation paths that go 0.5 to 1.8 kilometers farther inland than those experienced in 2004.

Key Words: tsunami, Banda Aceh, sea level rise, inundation, 2004 Sumatra-Andaman earthquake

INTRODUCTION

The M_w 9.1 to 9.3 Great Sumatra-Andaman Earthquake of December 26, 2004 produced the most devastating tsunami in recorded history, generating waves that were felt all over the world (Lay et al., 2005). Some of the greatest effects of this tsunami were experienced in the Banda Aceh region of northern Sumatra, Indonesia, where wave heights reached between 9 and 12 meters. The colossal devastation was due in part to the low-lying nature of Banda Aceh, which meant the tsunami obliterated over 80% of the city (Center for Satellite Based Crisis Information). Furthermore, the region's proximity to the Sumatra-Andaman fault meant that the tsunami came only 15-30 minutes after the initial earthquake, leaving little time for warning. As a result, the death toll in Banda Aceh is estimated to be over 125,000, which is over half the pre-tsunami population.

Several authors (Borrero et al., 2006; McCloskey et al., 2007; McCloskey et al., 2008) have assessed tsunami risk on Sumatra. Only one of these authors (Borrero et al., 2006) modeled tsunami inundation from possible future tsunamigenic seismic events, and this study was specific to two cities on the western coast of Sumatra. The two other studies are mainly concerned with modeling far-field wave heights and the nature of tsunami propagation in the Sumatra region.

This study develops a model to describe and assess the 2004 tsunami inundation in Banda Aceh. I then project inundation limits and flow heights for future tsunamis with initial wave heights of between 5 and 18 meters. Encompassed in this wave height estimate is an analysis of additional factors that would increase wave height beyond 2004 observations such as co-seismic subsidence and sea level response to climate change. To my knowledge, this is the first study to map the 2004 inundation and future inundations in Banda Aceh and also the first study to take sea level rise due to climate change and astronomical tides into account when projecting future tsunami inundation heights and extents.

This paper will first address the tectonic history and geology of the Banda Aceh region. It will then review tsunami modeling techniques and studies specific to the island of Sumatra. I then outline probable reasons for future sea level rise, discuss the origin of my data, and describe my methods. Results, discussion, and a conclusion follow.

TECTONIC BACKGROUND

Sumatra is a volcanic arc located on the overriding Eurasian plate at the convergent boundary between the Australian and Eurasian plates (Fig.1). This boundary extends southeast and north of the island, eventually connecting with the convergent boundary between the Eurasian and Indian plates (Fig. 1). On average, the Australian plate moves 68 mm/year northeast with respect to the Eurasian plate (Geist et al., 2006). In the area of Sumatra and the 2004 earthquake, the motion of the Australian plate is oblique but predominantly thrust and is converging with the Eurasian plate at a rate of 14 mm/year (Lay et al., 2005). The Great Sumatran Fault, a strike-slip fault, which extends through Sumatra, which helps to accommodate the oblique convergence of the Australian and Eurasian plates.

The epicenter of the 2004 earthquake was about 3.3˚N, 96.0˚E (Fig. 2), but the earthquake ruptured a 1,600 kilometer section of the plate boundary, which is the longest rupture length on record (Lay et al., 2005). Oblique-slip amplitudes of greater than 20 m were recorded in the Banda Aceh offshore region (Sladen and Hebert, 2008). The exceptionally large tsunami heights in Banda Aceh were due mostly to the proximity of the region to the epicenter as well as the large slip amplitudes experienced in the section of the fault near Banda Aceh.

Nalbant et al. (2005) suggest that the greatest future seismic threat in the Sumatra region is along the Mentawai section of the fault, between 0.7 and 5.5˚ S (Fig. 2). There is also risk of a seismic event of magnitude 7.0-7.5 north of 4˚N (Nalbant et al., 2005). Calculations along the Mentawai section suggest that the recurrence interval for this region is between 130 to 300 years. The last earthquake along the Mentawai section was in 1833, which indicates a future seismic event in this region is very likely. Given that this boundary is a subduction zone, the likelihood of a tsunami from an earthquake is high, although probably not one with the same global magnitude as in 2004.

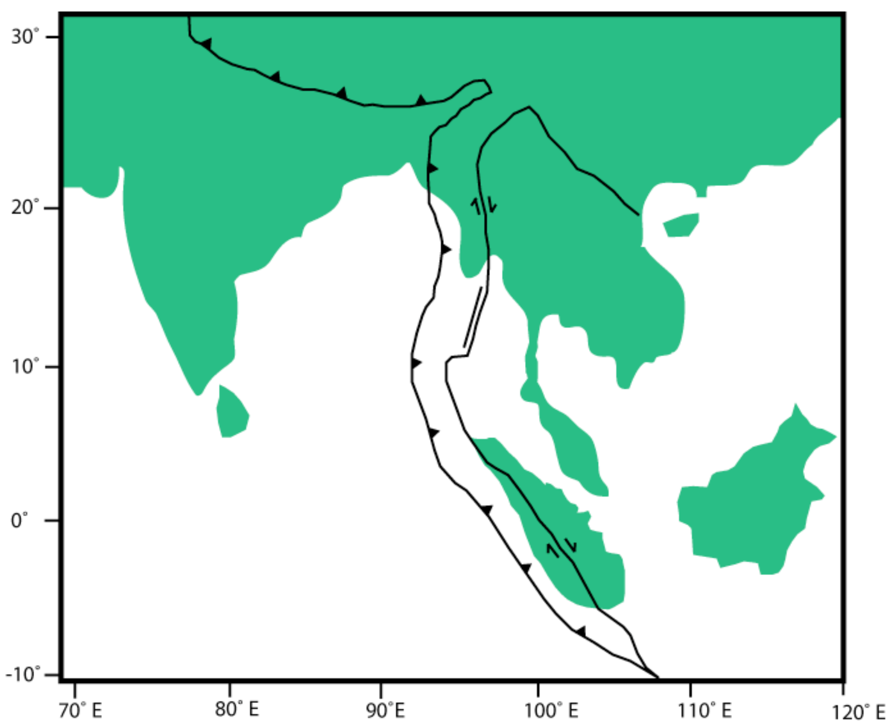

Figure 1. Major plate boundaries in central Asia.
Adapted from Lay et al., 2005

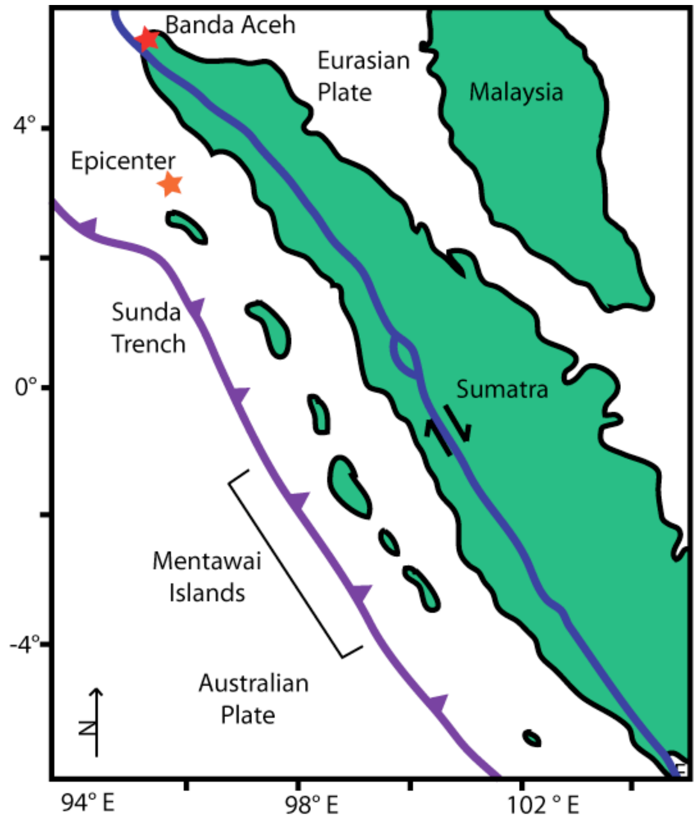

Figure 2. Location of fault system and 2004 epicenter with respect to Banda Aceh. The greatest furture seismic threat in this area is in the Mentawai region. Adapted from Nalbant et al., 2005.

GEOLOGIC BACKGROUND

The city of Banda Aceh sits on Quaternary terrestrial sediments of sandstone, shale and volcanics, and is surrounded by Quaternary volcanic rock and lower Cretaceous-upper Jurassic sediments (Barber and Milsom, 2005). It is situated on a river delta between two coastal headlands, which are as much as 200 m higher in elevation than the city (Fig. 3). The coastal headlands thus protect the area because they are more resistant to erosion and are significantly higher than the city. In contrast, the valley sediments are easily eroded and provide little protection from future tsunamis.

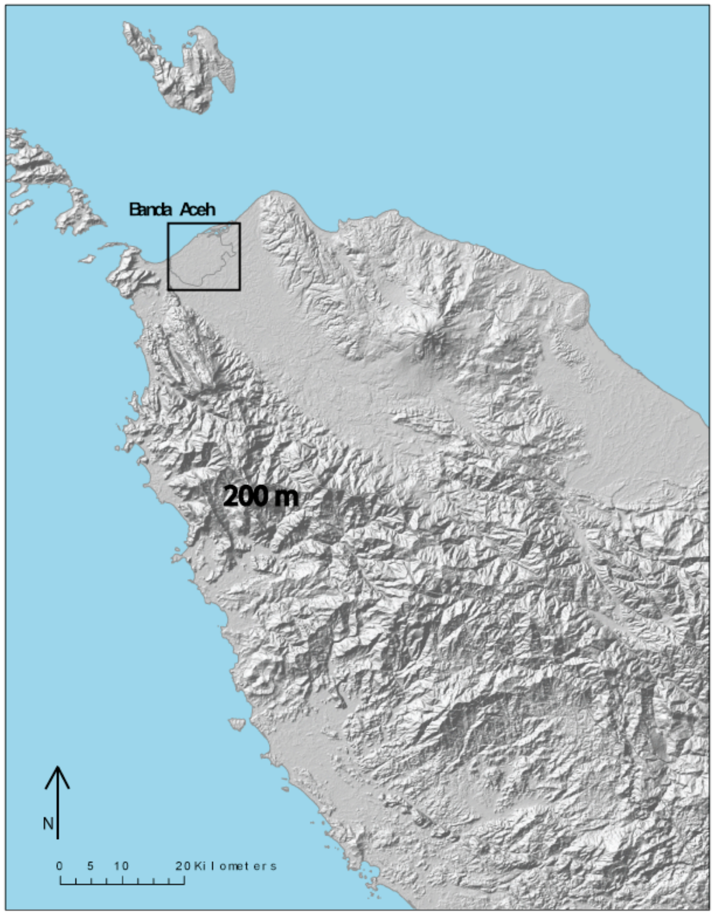

Figure 3. Digital elevation map of Banda Aceh with respect to the surrounding area. Boxed area notes area of study. Data courtesy of ESRI® Data & Maps, 2008 World

TSUNAMI MODELS

Tsunamis are impossible to predict, yet by understanding tsunami genesis and propagation, it is possible to model probable future tsunami paths and inundation extent. Tsunami wave generation is most effectively modeled from the vertical amount of coseismic displacement and the water depth above the source region. Moment magnitude and slip distribution are also used to understand tsunami magnitude, but these parameters are less effective in modeling near field wave heights (Geist et al., 2006; McCloskey et al., 2007).

Two types of models describe and predict tsunami generated wave heights: far field and near field models. Using information on fault characteristics and mathematical modeling, far field models focus heavily on understanding, modeling, and describing the most likely tsunamigenic seismic events. These models (Lovholt et al., 2006; McCloskey et al., 2007; Harig et al., 2008; McCloskey et al., 2008) then use ocean bathymetry information to predict or describe observed coastal wave height maxima. In contrast, near field models focus on mapping inundation for a specific city or stretch of coast (Priest, 1995; Suleimani et al., 2003; Borrero et al., 2006; Wijetunge et al., 2008). Near field models depend on local bathymetry phenomena such as wave refraction, partial reflection off sharp changes in bathymetry, and wave trapping (Geist et al., 2006).

Far field and near field models can be used for both retroactive and proactive modeling. The goal of retroactive modeling is to advance our modeling capabilities by modeling past events such as the 2004 Sumatra event (Harig et al., 2008; Wijetunge et al., 2008) or the 1964 Kodiak Island event (Suleimani et al., 2003). These studies are also useful for city and evacuation planning. Proactive modeling projects scenarios that are likely to occur in the future (Priest, 1995; Borrero et al., 2006; Lovholt et al., 2006). This paper is a near field, proactive study and new to the literature because while most models take co-seismic subsidence into account, no model has included the additional effect of sea level rise as part of inundation modeling.

There are two proactive far field studies (McCloskey et al., 2007; McCloskey et al., 2008) and one proactive near field study (Borrero et al., 2006) for the island of Sumatra. No near field studies exist for the city of Banda Aceh or for any portion of northern Sumatra's coast.

McCloskey et al. (2007) focus mainly on source modeling to derive far field (defined as 10 or more meters from the coast) wave heights for various cites on Sumatra. These authors modeled 1,000 possible earthquake scenarios for the Sumatra region and then chose the most 100 likely to occur earthquakes based on geodetic evidence. Consistent with the results of Nalbant et al., 2005, McCloskey et al. (2007) find that the area most likely to rupture is the Mentawai region, but they note that the tsunamigenic potential of any given earthquake is more difficult to calculate, as tsunami genesis depends on the unpredictable details of slip distribution. Specifically for the city of Banda Aceh, McCloskey et al. (2007) report that the maximum wave height for all 100 earthquake scenarios is 0.4 m, which is small in comparison to the 15-18 m maximum heights they predict for the southwestern coast. This is because the Mentawai region is significantly farther south than the 2004 rupture zone, and thus regions of southwest Sumatra will experience larger wave heights in comparison to northern Sumatra under the 100 most likely earthquake scenarios.

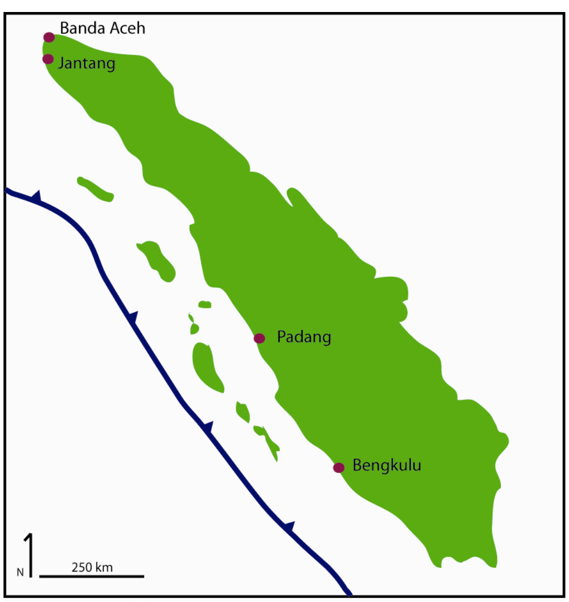

Figure 4. Locations of Sumatran cities

Borrero et al. (2006) modeled inundation from future seismic events on the Mentawai section along the coast of western Sumatra, specifically for the cities of Padang and Bengkulu (Fig. 4). This study employed the computer model MOST, which produced a grid with a resolution of 200 m in the cities and 1,200 - Using information on modeled levels of seismic subsidence, near shore topography, and coastal bathymetry to model tsunami propagation, Borrero et al. (2006) report flow depths in these regions of between 1 and 4 m and inundation distances of between 0.4 and 1.5 km from the coast.

SEA LEVEL RISE

To model future tsunami inundation heights and paths, I assume a 3 m sea level rise compared to the 2004 sea level height in Banda Aceh. This 3 m encompasses 2 m due to subsidence, 0.53 m due to tidal cycles and 0.47 m due to climate change related sea level rise.

Astronomical Tides

Banda Aceh experiences 0.6 m to 1.3 m semidiurnal tides, depending on spring or neap tide cycles (Tsuji et al., 2005b). The 2004 tsunami hit while tides were 22 to 44 cm below high tide during a neap tide (Tsuji et al., 2005b). For the purposes of this study, I assume that a future tsunami will hit the Sumatran coast at high tide but not during a spring tide. Thus, I assume a future tsunami will hit the Banda Aceh coast 53 cm above the tide level it hit in 2004.

Subsidence

Three to four months after the 2004 earthquake, Jaffe et al. (2006) measured subsidence of up to 2 m on Sumatra due to this event. Jaffe et. al (2006) did not measure subsidence in Banda Aceh, but did take two measurements in Jantang, which is to the southwest of Banda Aceh (Fig. 4). All other post earthquake subsidence measurements were taken in southern Sumatra and are not useful for this study because subsidence varies heavily with distance from the fault.

Figure 5. A member of the International Survey Team measuring subsidene in Sumatra. Photo courtesy of the USGS

To measure observed subsidence, Jaffe et al. (2006) measured the depth below current sea level of root balls of living palm trees and consulted eyewitnesses. The palm tree method assumes that the root balls of palm trees do not grow below the salt water table, so their depth below sea level at the time of measurement is equal to the minimum subsidence that occurred (Fig. 5). The eyewitness method used a combination of local residents' memories of the former position of the shoreline as well as slope calculations. Subsidence in this area was measured twice, once as 0.6 m and once as 2.0 m, but due to the method used, the 2.0 m measurement is considered by the authors to be more accurate. I estimate error in subsidence measurements to be ± 0.5 m. Based on this information from a field survey after the 2004 event, I expect that a future earthquake will cause subsidence of up to 2 ± 0.5 m in Banda Aceh.

Climate Change

Mechanisms

Global average sea level is expected to rise over the coming centuries due to climate change, and indeed a global sea level rise of 1.7 ± 0.5 mm/yr has already been observed over the twentieth century (Meehl et al., 2007). Sea level is rising due to thermal expansion of the warming water and increased volume from melting ice caps, glaciers and ice sheets.

Thermal expansion accounts for the majority (70-75%) of this rise, but is not spatially uniform. Some areas, such as the Western Pacific Ocean, have experienced much higher levels of sea level rise than the global average (Meehl et al., 2007). Such regional variation is due to non-uniform changes in ocean heat content (Nerem et al., 2006). While melting from ice caps, glaciers, and ice sheets has contributed little to sea level rise relative to thermal expansion, a collapse of one or more ice sheets has the potential to raise global sea level more than thermal expansion ever could. For example, a collapse of the West Antarctic Ice Sheet could raise global sea level by 5 m (Meehl et al., 2007), although present scientific understanding cannot predict the speed or likelihood at which this could happen.

Data Collection

Documentation of sea level rise occurs in two ways: tide gauges and satellite altimetry.

Worldwide tide gauge data is compiled by The Permanent Service for Mean Sea Level (PSMSL) from monthly and annual mean values reported from over 1,900 gauges under the jurisdiction of 200 national authorities (The Permanent Service for Mean Sea Level, 2003; Woodworth and Player, 2003). The PSMSL then performs checks on the data and compiles the Revised Local Reference (RLR) dataset. The RLR dataset is the only dataset that should be used for time series analysis because the method of compilation ensures datum continuity. While tide gauge error varies from station to station (Intergovernmental Oceanographic Comission, 2006), for the purpose of this study, I assume an overall error in data from tide gauges of ± 10 mm (P.Woodworth, Pers. Com).

Sea level rise is also measured by the TOPEX/Poseidon satellite, which NASA launched in 1992 tto collect ocean topography and sea level data (NASA, 2008). The satellite repeats the same path every ten days at 0 ± 66° latitude (NASA, 2008). After standard corrections, the TOPEX/Poseidon satellite altimeter has an error of ± 80 mm for one measurement or ± 8 mm for along-track averages (Bindoff et al., 2007).

Models

To model global and regional sea level rise, a number of Atmosphere-Ocean Global Circulation/Climate Models (AOGCMs) are used. Each AOGCM measures sea level rise as a response to modeled future climate, which is dependent on scores of variables. Although most models follow the Intergovernmental Panel of Climate Change (IPCC) scenario IS92a, which assumes future mid-range economic growth but no measures to reduce fossil fuel emissions, the models differ from each other in areas such as how individual trace gasses are specified, how CO_2 emissions are compounded, how sulfate aerosols are treated, and the inclusion of tropospheric ozone (Gregory et al., 2001).

Sea Level Rise in the 20th and 21st Centuries

Globally

Average rates of global sea level rise reported in the Fourth Assessment Report of the IPCC are 1.8 ± 0.5 mm/yr for the period 1961-2003 and 3.1 ± 0.7 mm/ yr for 1993-2003 (Bindoff et al., 2007). It is unknown whether the higher rate observed in the last decade of the twentieth century indicates decadal variability or an increase in the rate of sea level rise. Projections for global average sea level rise range from an increase of 280 ± 5 mm to 430 ± 08 mm from 1999 levels by the end of the twenty-first century, depending on which SRES[1] scenario is used in the AOGCM (Bindoff et al., 2007). In all scenarios, however, the rate of average global sea level rise is projected to exceed the rate observed during 1961-2003.

Regionally

Regional models for sea level rise are less developed than global models, mostly because the current models do not resolve small scales well. Additionally, the models become much more sensitive to initial conditions and parameterizations, which have large error associated with them at the regional scale (R. Thieler, Pers. Comm). Global sea level projections are inadequate for understanding regional sea level rise, however (Church et al., 2004; Church et al., 2006; Landerer et al., 2006). As indicated in Figure 6, regional sea level change ranged from -15 mm/yr to 15mm/yr between 1950 and 2000, whereas the global average was 1.8 ± 0.3 mm/yr for this same period (Church et al., 2004). Departure from the change in global average sea level in any given region may be due to one or all of the following reasons: changes in ocean circulation and wind, changes in surface atmospheric pressure, and isostatic rebound associated with ice melt.

Regional sea level rise in the Sumatra region over the period 1950-2000 was 3.6 mm yr^{-1}, which twice the global average (Fig. 6). This regional anomaly may be due to changes in winds in the Indian Ocean or to effects of El Niño Southern Oscillation, but the reason for this large departure from the global average is not known with any

[1] Special Report on Emissions Scenarios from the IPCC Third Assessment Report. Each emissions scenario is based on varying levels of economic development, environmental values, the carbon efficiency of the world economy, and the extent of globalization.

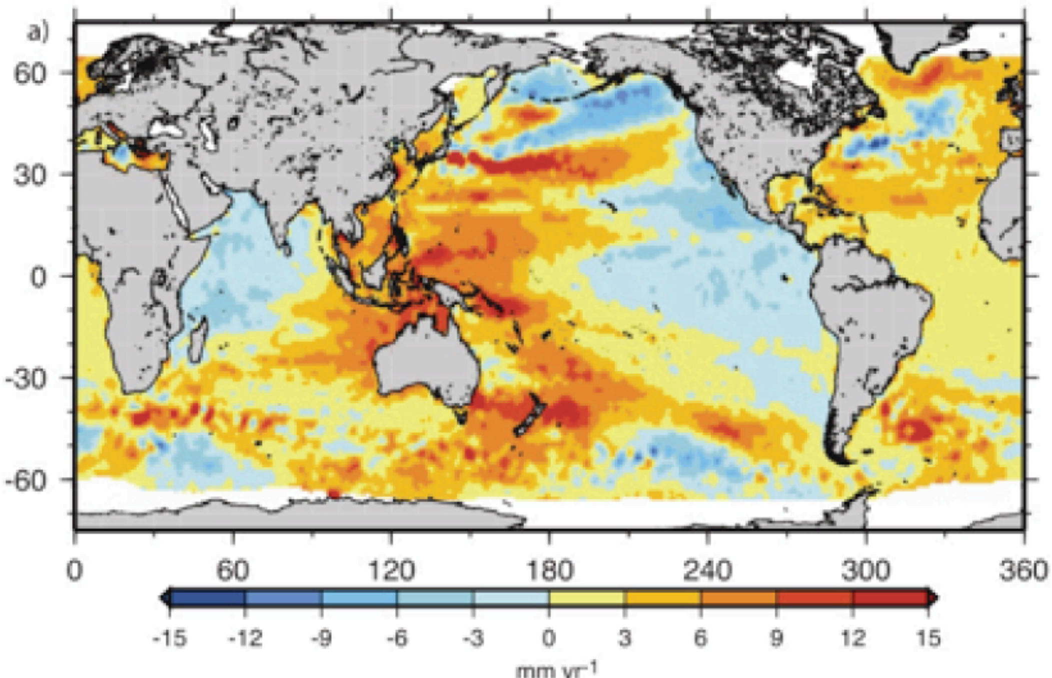

Figure 6. Geographic distribution of short-term linear trends in mean sea level (mm yr^{-1}) for 1993 to 2003 based on TOPEX/Poseidon satellite altimetry. Reproduced from Bindioff et al., 2007 figure 5.15, which was updated from Cazenave and Nerem, 2004

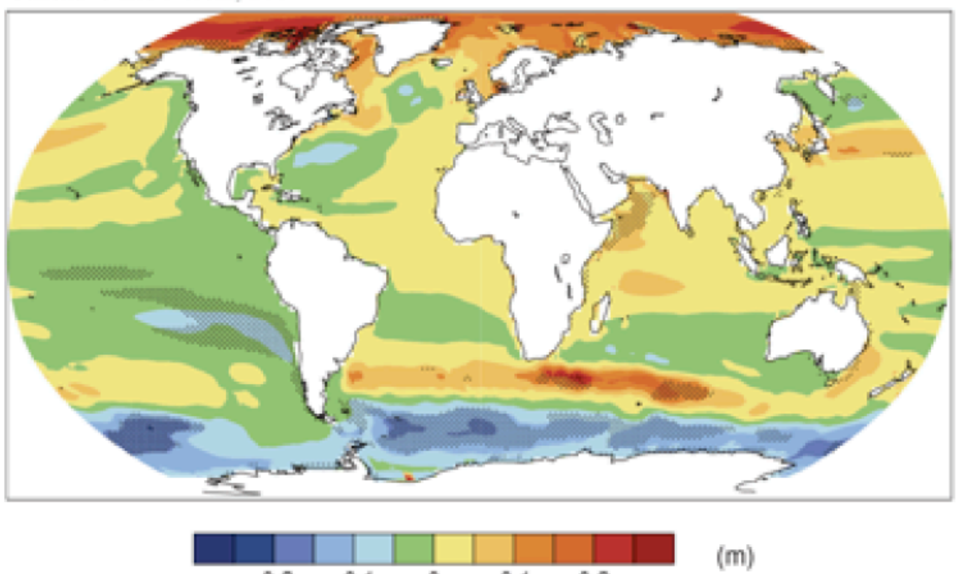

Figure 7. Local sea level change (m) due to ocean density and circulation change relative to the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century, calculated as the difference between averages for 2080 to 2099 and 1980 to 1999, as an ensemble mean over 16 AOGCMs forced with the SRES A1B scenario. Stippling denotes regions where the magnitude of the multi-model ensemble mean divided by the multi-model standard deviation exceeds 1.0.
Reproduced from Meehl et al., 2007, figure 10.32

certainty (J. Church, Pers. Comm). Despite the fact that past sea level rise has been high around Sumatra for the later part of the twentieth century, Meehl et al. (2007) project that sea level in the twenty-first century will rise a total of at most 50 mm above the global average (Fig. 7). This discrepancy may be because the twentieth century anomaly around Sumatra is due to natural variability, in which case sea level may not rise at such anomalous rates in the future.

For the purposes of this study, I assume projected sea level rise due to climate change in the Sumatra region to be 470 ± 8 mm by 2099, or the highest projected global average added to the regional variation in sea level rise in Sumatra as projected by Meehel et al. (2007). I use the scenario with the highest projected sea level rise so that the worst possible tsunami inundation is calculated and Banda Aceh is prepared for the next tsunami.

DATA

The first post-tsunami survey of inundation heights in Banda Aceh was collected by Tsuji et al. in January 2005. At the time of the survey, Banda Aceh had not significantly recovered from the tsunami and navigating around the city was exceptionally difficult (A. Moore, Pers. Comm). For this reason, the Tsuji et. al team was only able to measure inundation heights along accessible roads. Fig. 8 indicates the location of the 28 measurements taken by this team. Each of these inundation heights was measured by water marks left on buildings, bark stripped off trees, and broken tree branches (USGS, 2005). I estimate the error due to human measurement to be ± 5 cm.

The second post-tsunami survey was funded by the Embassy of Japan in the Republic of Indonesia. The data, reported by Iemura et al. (2008) were collected by local

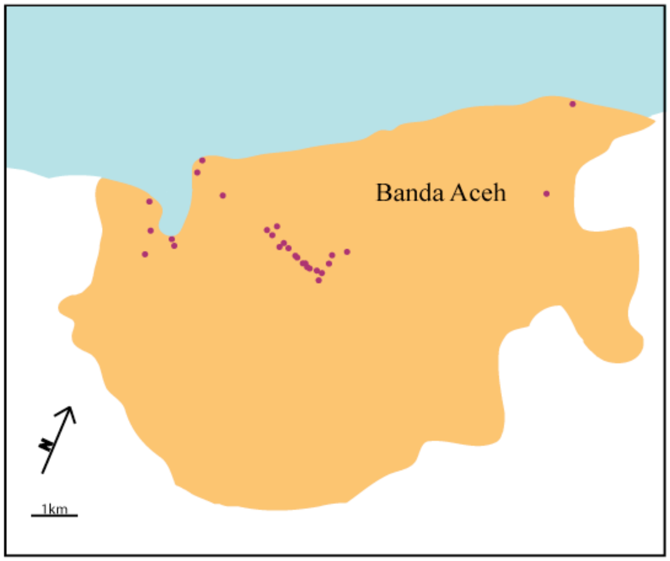

Figure 8. Location of tsunami inundation height measurments taken by Tsuji et. al (2005a)

Figure 9: A Tsunami Memorial Pole in Banda Aceh

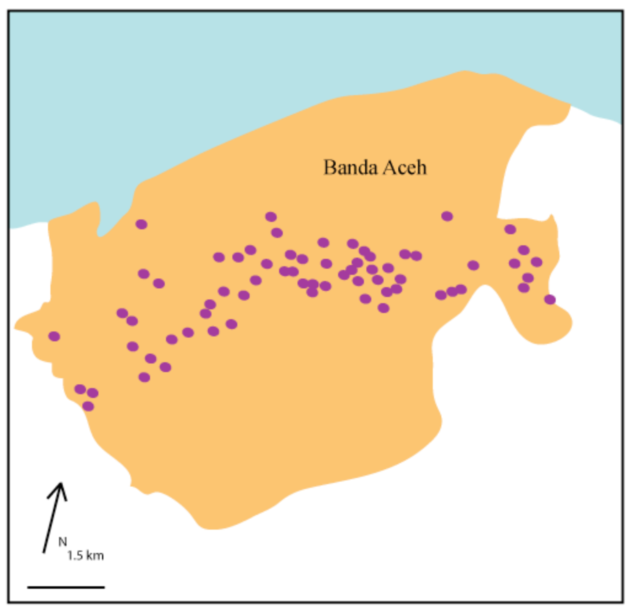

Figure 10: Location of tsunami height measurments compiled by Iemura et al. (2008)

and international scientists by measuring watermarks on buildings and interviewing local residents. These data were then used to construct Tsunami Memorial Poles showing the height of the 2004 tsunami (Fig. 9) along tsunami evacuation routes in Banda Aceh. I estimate the error due to human measurements and memory in this case to be ± 15 cm.

The data compiled by Tsuji et al. (2008a) are less extensive but measure more data points close to shore and indicate larger initial wave heights than the Iemura et al. (2008) data (Fig. 10). For analysis, I use the more comprehensive Iemura et al. (2008) data but manipulate model conditions with attention to both sets of data. More details are provided below.

METHODS

To understand where a future tsunami might inundate, I model how the 2004 tsunami inundated Banda Aceh by examining the relationship between distance from shore and inundation heights as reported in the data set compiled by Iemura et al. (2008). Topography was not taken into account in the model because no published topographic maps with resolution higher than 25 m contour intervals exist for Banda Aceh. The error associated with Google Earth elevation measurements is large enough such that the model is more accurate when elevation is not included. Furthermore, the terrain in Banda Aceh is flat enough such that dissipation of wave energy can accurately be described as a function of distance from shore.

I model tsunami inundation in two ways: with a linear and an exponential model. The linear model is created by doing a linear regression on the wave height data from Iemura et al. (2008) (Fig.11). The residuals (Fig. 12) indicate that a linear model is appropriate for this data. The linear model for the Iemura et al. (2008) data intercepts the y-axis at approximately 8 m, indicating maximum wave heights were 8 m. This is much lower than the maximum wave height of 12 m reported by Tsuji et al. (2008a). Given this discrepancy in maximum wave heights, it is possible that tsunami inundation in Banda Aceh can be modeled exponentially (Fig. 13). The residuals from this model are presented in Figure 14.

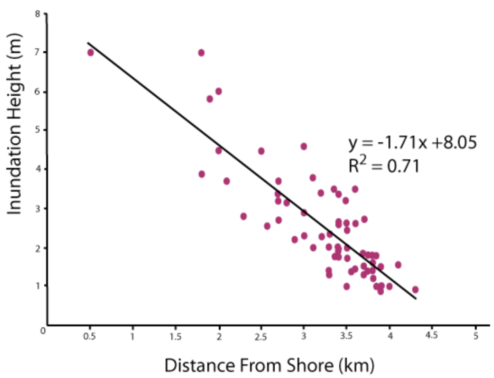

Figure 11. Linear regression for the data compiled by Iemura et al., 2008. Note that this model fits the data at greater distances from shore better than the data points closer to the coastline. This is most likely due to variance in initial wave heights from local bathymetry. As the wave encounters the land, however, inundation heights become more uniform.

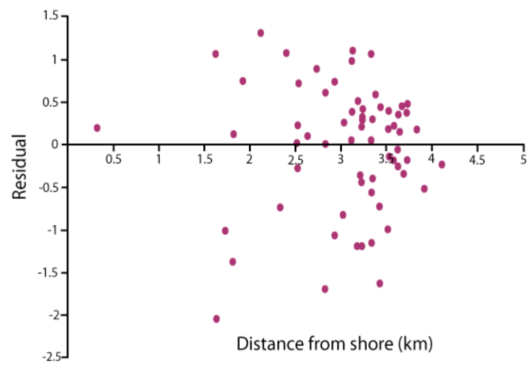

Figure 12. Residuals for the linear model described in Figure 11. Note that the residuals are clumped around the larger X values. This reflects the large number of data points measured farther from shore. As shown in Figure 11, the linear model fits these points better than the measurements closer to shore, which is why the residuals are closer to zero for larger values of X.

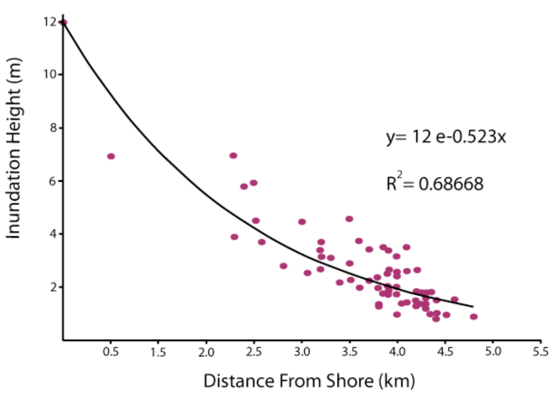

Figure 13. Exponential model of Iemura et al., 2008 with initial wave height of 12 m, as reported by Tsuji et. al, 2005.

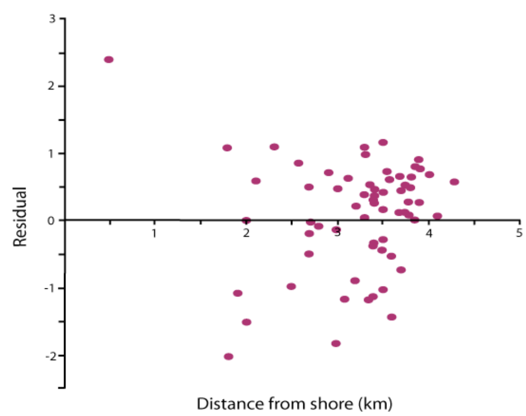

Figure 14. Residuals for the exponential model described in Figure 13. Note that the residuals are clumped around the larger X values. This reflects the large number of data points measured farther from shore. These residuals are more scattered than the residuals for the linear model. For this reason, the linear model may be more appropriate.

To model future tsunami inundation, I test three scenarios with differing maximum wave heights. First, far field wave heights are the same as in 2004 but there is a 3 m rise in sea level relative to 2004 levels due to climate change, subsidence, and high tide. Under this scenario the maximum wave height is 15 m, which is sea level rise of 3 m added to the 12 m 2004 inundation height as reported by Tsuji et al. (2008a). Second, I model a maximum wave height of 11m, which is sea level rise of 3 m added to the 8 m maximum 2004 inundation height as predicted by the Iemura et al. (2008) data. Third, far field wave heights are 3.4 m, which is sea level rise of 3 m added to the 0.4 m far field heights modeled by McCloskey et al. (2007) for an earthquake in the Mentawai region.

These scenarios are run through the linear and exponential models. The 8 and 11 m scenarios were not run through the exponential model because the maximum wave height of 8 m was found using the linear model. The heights 8, 11, 12, 15, and 3.4 m represent initial wave heights—the wave height when distance from shore is zero. This is also the y-intercept of the linear model and the coefficient of the exponential model. To model future inundation, I manipulate the y-intercept and coefficient of the existing models to plot future inundation (Fig. 15). This information was then spatially plotted using Geographic Information Systems (GIS) technology.

Consistent with the work of Kench et al. (2008), I assume no major change in costal morphology due to the 2004 tsunami or unpredictable processes that may occur in the future. I also assume that significant subsidence does not occur between tsunamigenic events.

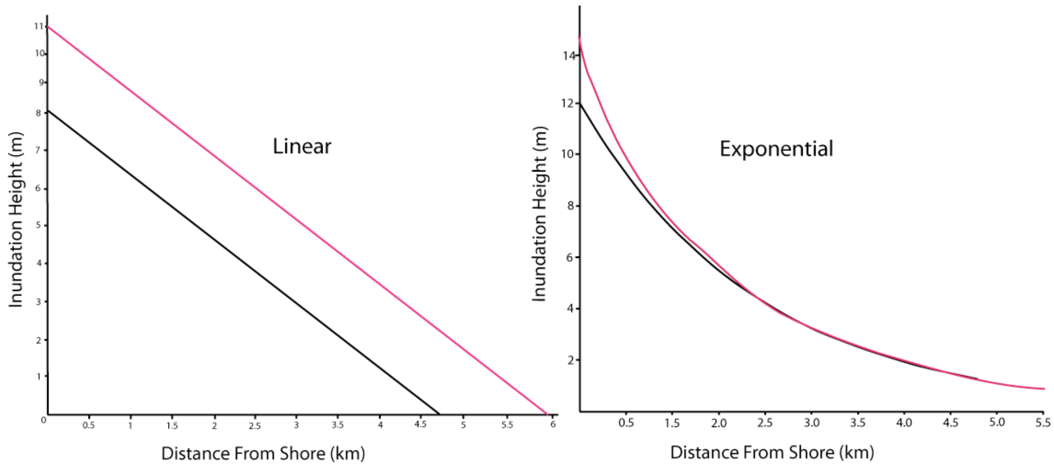

Figure 15. Visual representation of modeling technique. The lower line in each graph is the existing model and the upper line is Future inundation given a 3 m sea level rise.

RESULTS

The results of these simulations are reported in Figure 16. It is clear that a 3 m sea level rise (8 m vs. 11 m or 12 m vs. 15 m) causes inundation to go significantly farther inland. More specifically, whereas the 2004 tsunami did not inundate to the city limits, the same tsunami with additional sea level rise would inundate to farther than the city limits, further putting the Banda Acehan population at risk. The specifics of each model are discussed below. Sensitivity to initial parameters is reported in Table 1.

Linear Model

Under the linear model, a 1 m change in initial wave height results in 0.6 km change in inundation extent. If a future tsunami of the same magnitude as in 2004 occurs during low tide, then tsunami inundation extent might only be 7.9 km as opposed to 8.5 km if the tsunami occured during high tide. Similarly, if subsidence of up to 1 m occurs between tsunamigenic events, inundation might go as far as 9.1 km inland. Note that under the linear model, a sea level rise of 4 m, combined with the most likely to occur

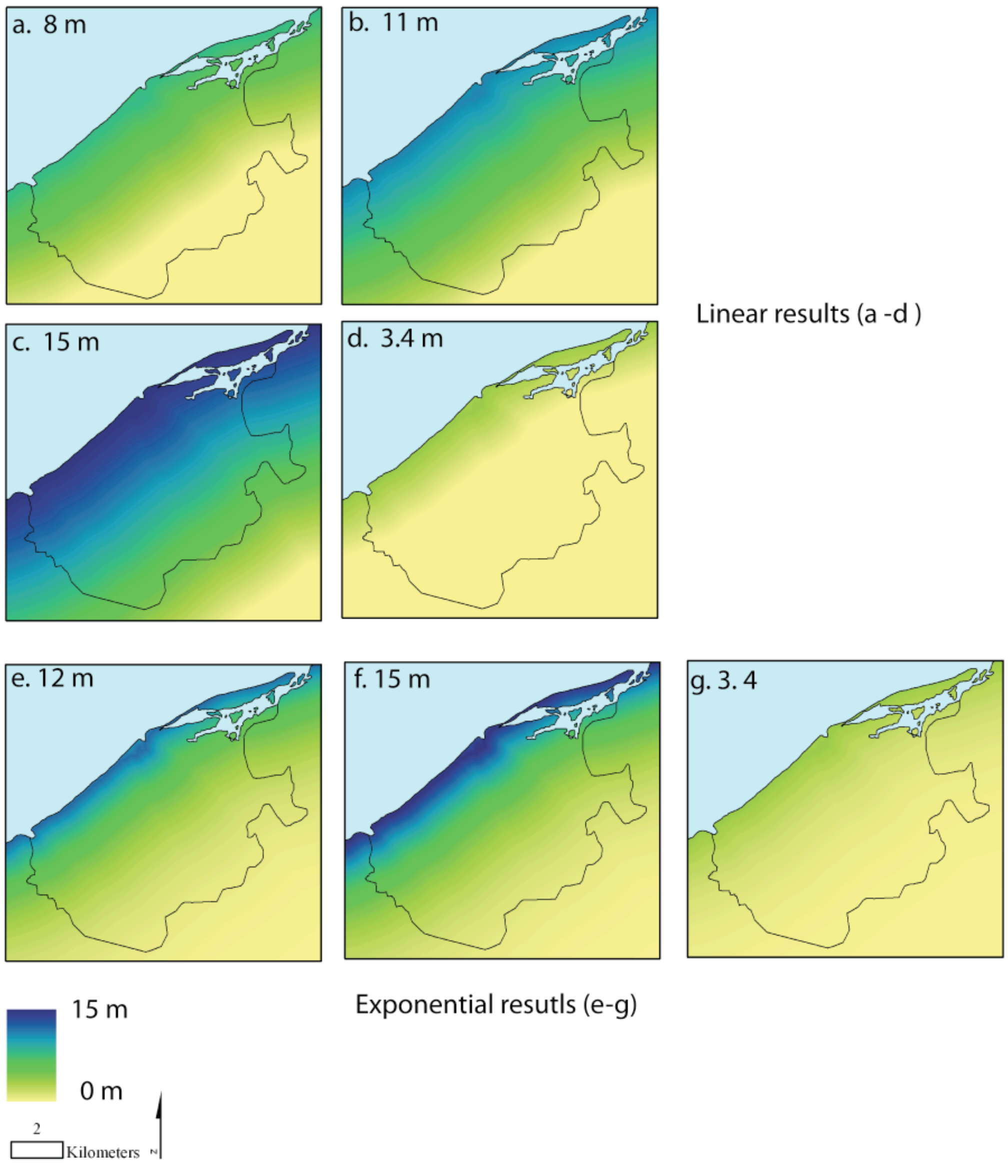

Figure 16. Modeled tsunami height for Banda Aceh. The box in Figure 3 corresponds to the boxes in this figure. a-d follow the linear model, e-g follow the exponential model. Cell size is 3 m. Initial wave height is indicated in the top left corner of each square. Boxes a and e represent 2004 modeled inundation. Data courtesy of the National Geospatial-Intellegence Agency, Prototype Global Shoreline Data

future tsunami (base height of 0.4 m), results in an inundation distance only 2.4 km shorter than what may have occurred in 2004.

Exponential Model

As indicated in Table 1, inundation extent under the exponential model for all scenarios is between 2.1 km and 7.1 km, whereas the range for linear model is between 0.5 km and 9.1 km. This means inundation extent under exponential model is much less sensitive to initial parameters than the linear model. Furthermore, while initial parameters in the exponential model dictate variation in inundation height for the first 4 km inand, there is not nearly as much variation in inundation height beyond this point as in the linear model.

	Linear Model			Exponential Model		
	12 m	8 m	0.4 m	12 m	8 m	0.4 m
4 m	9.1 ± 0.5	6.7 ± 0.6	2.3 ± 0.5	7.1 ±1.0	6.5 ±1.0	4.4 ±1.0
3m	8.5 ± 0.5	6.1 ± 0.6	1.7 ± 0.5	7.0 ±1.0	6.3 ±1.0	3.9 ±1.0
2 m	7.9 ± 0.5	5.6 ± 0.6	1.1 ± 0.5	6.8 ±1.0	6.1 ±1.0	3.2 ±1.0
1 m	7.3 ± 0.5	5.0 ± 0.6	0.5 ± 0.5	6.7 ±1.0	5.9 ±1.0	2.1 ±1.0

Table 1: Inundation extent (km) under the linear and exponential models for varying amounts of sea level rise (vertical axis) and base wave heights (horizontal axis). In all cases, "inundation extent" is defined as 0.5 m water height so that values are obtainable for the exponential model. 0.5 m is appropriate because water at this level will not cause structural damage to a building nor will it put human life at significant risk.

DISCUSSION

Given the limited amount of data documenting the 2004 inundation, and the fact that neither of the data sets have points that measure inundation heights of 0.5 m or less, the total extent of inundation in 2004 is unknown and therefore it is impossible to determine which model is most appropriate.

Both the linear and the exponential model assume a tsunami will inundate perfectly perpendicular to shore. While there are not enough data to demonstrate that the 2004 tsunami inundated in this way, this method is consistent with other near field tsunami models (Priest, 1995; Borrero et al., 2006). If tsunami propagation and inundation is not perpendicular to the shore and, correspondingly, if local bathymetry is such that initial wave heights vary along the coastline, inundation would not be uniform as projected with these models. If inundation in Banda Aceh is indeed oblique, this could also explain why the maximum inundation height reported by Tsuji et al. (2005a) is higher than that reported by Iemura et al. (2008), as the Tsuji et al. (2005a) point was measured west of the Iemura et al. (2008) point.

The results presented in Figure 16b and 16c both assume a sea level rise of 3 m and a base wave height comparable to that in 2004. Figure 16b assumes an 8 m base wave height, as expected from the Iemura et al. data (2008) whereas Figure 16c assumes a 12 m base wave height, according to the Tsuji et al. (2005a) data. In both data sets, there are few measurements directly on the coast (Figs. 8, 10) and thus it is impossible to extrapolate absolute initial wave heights. Given that the Tsjui et al. (2005a) data were collected in the month following the tsunami and before rebuilding began whereas the Iemura et al. (2008) data were collected later, it is probable that the Tsuji et al. (2008a) data more accurately document the 2004 inundation. It is likely, therefore, that Figure 16c is more probable.

This study focuses on modeling the 2004 inundation and how sea level rise will affect tsunami inundation if a future tsunami is the same magnitude as observed in 2004. However, it is important to highlight Figures 16d and 16g, which model inundation assuming the maximum height of the most likely to occur tsunamis, as modeled by McCloskey et al. (2007). Under this scenario, inundation extends up to 1.7 km under the linear model and up to 3.9 km under the exponential model. While Banda Aceh is significantly farther north than the cities of Padang or Bengkulu and thus any tsunami will inundate the three cities to different extents, the results for the inundation extent of the most likely tsunami reported in this study are on the same order of magnitude as those reported for similar scenarios in Padang and Bengkulu by Borrero et al. (2006).

CONCLUSION

The fact that Banda Aceh is built on a flood plain makes the region highly susceptible to devastation from a future tsunami. Without climate change, the region is likely to face severe damage from another tsunami, but global warming will intensify this risk. In planning for the next tsunami, climate change and subsidence must be taken into account so that the loss of human life and infrastructure is minimized. Finally, while the results of this study certainly cannot predict tsunami inundation for any given event, they can help local emergency management teams plan and prepare for the next tsunami in Banda Aceh.

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